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High-Capacity Radio Communication for the Polar Region: Challenges and Potential Solutions

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Abstract

The melting of the Arctic glaciers is resulting in the opening of major transportation routes, such as the Northwest, Northeast and North-North Passages. With increasing shipping traffic and activities related to the fishing, oil, and gas industries, the need for reliable communication systems in the polar region is very high. In this paper, we discuss the communication challenges and limitations in the polar region, and study the different technologies that might be used. In addition to using geostationary, high-elliptical-orbit, and low-Earth-orbit satellites, low-cost alternatives, such as a store-and-forward method using polar-orbiting satellites, high-frequency multiple-input multiple-output (HF MIMO), and wide-area mesh network solutions, are proposed. Depending on the type of service to be provided and the budget needed to roll out and operate the system, operators may choose one of the proposed communication solutions for the polar region.

Keywords: Polar region; propagation; satellite communication; HF MIMO; mesh network; store-and-forward; HF radio propagation

1. Introduction

According to the US Geological Survey [1], due to climate changes, the Arctic glaciers are melting more rapidly than previously known. This leads to the opening of new transportation routes, such as the Northwest and Northeast (northern sea route) Passages (see Figure 1). Further melting of the glaciers may also lead to the opening of the North-North Passage (the dashed line in Figure 1). It is reported that 22% of the world's petroleum resources might be in the Arctic [1]. With increasing ship traffic combined with activities related to fishing, oil, and gas exploration, we may expect an increasing demand for high-capacity communication services in the polar region.

A high-capacity communication system in the polar region could provide services to ships, oil, and gas installations, and could support other maritime activities, such as monitoring and surveillance. Shipping traffic is expected to increase as major transportation routes are opened for traffic. The navigation conditions in these areas will be demanding, due to icing, drifting ice, fog, high seas, and strong winds [2]. This requires a communication system with enhanced vessel-traffic monitoring, weather-forecast capabilities, and early warning of possible dangerous situations.

The increasing activity in the oil and gas industries in the polar region may raise the probability of disasters, such as oil spills from takers, or blowouts from oil installations. A high-capacity communication system, capable of monitoring, detecting, and reporting oil spills (using, for example, wireless sensor networks in the vicinity of oil installations, placed below and/or above the water's surface) to reduce environmental pollution is highly desirable. Furthermore, the increasing human activities and changing climate in the polar region may have a negative influence on marine resources. A communication-monitoring system that provides information on the temporal and spatial distribution of marine resources might be used for better control and management of marine resources.

Satellite communication is suitable for many users spread over a large area. By utilizing three satellites in the Molniya orbit (high-elliptical-orbit, HEO), full coverage from around 52° to 90° north can be obtained. In this case, user terminals are required to have a tracking antenna, due to mainly north-south motion of the satellites. In addition, presently existing low-Earth-orbit (LEO) satellite systems, such as Iridium, could be used for communication in the polar region, but the maximum offered capacity is low. The data rate is expected to increase with the second generation of the Iridium system. However, the connection cost may still be expensive. Alternatively, a geostationary (GEO) satellite can be used, but coverage is limited to up around 75° to 81° north (depending on the elevation angle) due to the Earth's curvature. Usually, most practical systems have a minimum elevation angle of around 2°, resulting in a geostationary-satellite-coverage limit to up around 79° north. In general, satellite connections are expensive, and thus designing a low-cost high-capacity heterogeneous (satellite and terrestrial) communication system solution might be desirable.

Figure 1. The opening of new transportation routes as the Arctic glaciers melt due to climate changes.

In this paper, we study the challenges and limitations of providing low-cost broadband communication system solutions to the polar region, and discuss the different technologies that might be used. The challenges and limitations are discussed in Section 2. Potential solutions and comparisons are presented in Sections 3 and 4, respectively. Finally, conclusions are given in Section 5.

2. Communication Challenges

2.1 Terrestrial Systems

Terrestrial communication systems, operating on frequency bands such as high frequency (HF) or very high frequency (VHF), etc., have some limitations for use in the polar region. The refraction and reflection of HF signals (between 3 MHz and 30 MHz) by the ionosphere (50 km to 500 km altitude) and the Earth's surface allows long-range communication to be achieved. Parts of the transmitted HF signal propagate along the sea's surface, following the Earth's curvature beyond the horizon [3]. This form of signal propagation is not limited to a single hop. Many hops are possible, depending on the condition of the ionosphere, as well as the Earth's surface where the signal is reflected [4] (see Figure 2). However, the availability of such links would be limited due to observation limitations and fading caused by particle radiation, which may last for several days. Furthermore, the capacity offered by a single-input single-output (SISO) HF signal is low. Presently, the largest concentration of shipping vessels is near the coast (less traffic longer on the sea). For maritime communication purposes, a VHF radio with a range of 100 km to 130 km might thus be used (higher frequencies have range

limitations). However, the distribution of marine traffic is expected to change when the Polar Sea – especially the North-North Passage – is open for transportation (see Figure 1). The challenge for covering the polar region then still remains.

2.2 Two-Satellite Systems

The true broadcast nature of satellite-based communication offers great advantages in delivering multicast and broadcast services for both populated and isolated areas. A Molniya orbit, often referred to as a HEO, is an egg-shaped orbit inclined 63.4° to the equator, with a high apogee over the northern hemisphere and a low perigee over the southern hemisphere. Using three satellites in the Molniya orbit, full coverage from around 52° to 90° north can be obtained. Owing to the high eccentricity of the orbit, a satellite will spend about two-thirds of the orbital period near apogee (the high point). After this period, a switchover to another satellite is performed [5]. Due to the north-south motion of the satellites, there is a need for constantly tracking the satellite, and compensation for the signal-loss variations. This results in a complex control system and expensive Earth terminals.

Due to the spherical shape of the Earth, the coverage of a geostationary satellite (positioned above the equator) is limited to up around 75° to 81° north (depending on the elevation angle). The dashed circles in Figure 3 show the areas in the polar region not covered by a geostationary satellite when the elevation angles are 0° and 5°, which are achieved for locations at around 75° and 81° north, respectively (see Figure 3). Generally, for low elevation angles, there is a considerable

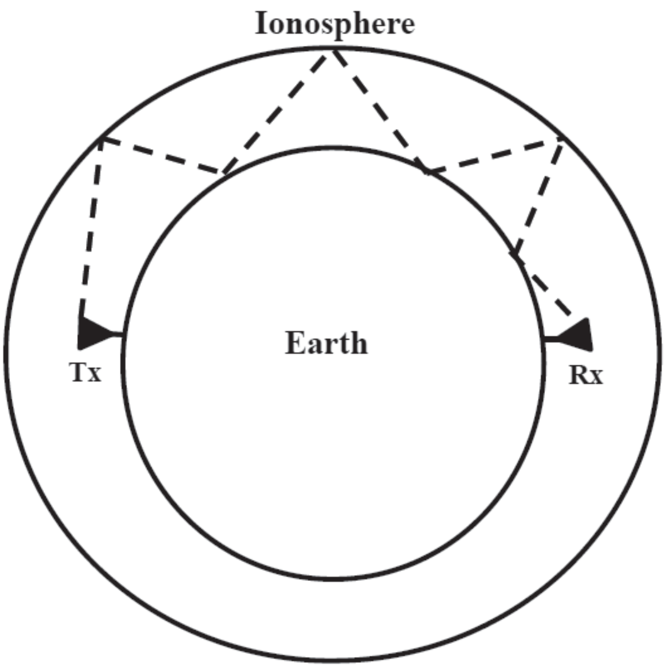

Figure 2. The refraction and reflection of an HF signal by the ionosphere and the Earth's surface, allowing long-range communication. TX and Rx are the transmitting and receiving antennas, respectively.

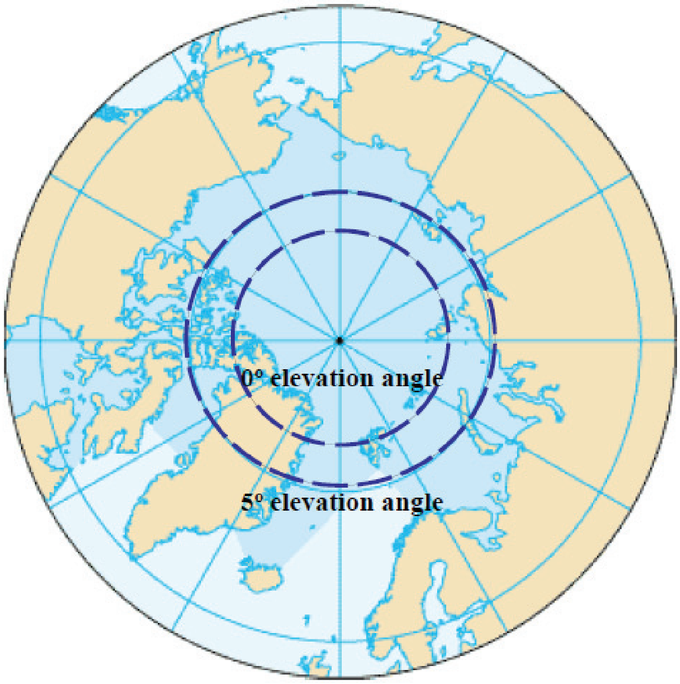

Figure 3. The area of the polar region not covered by a geostationary satellite when the elevation angle is 0° and when it is 5° (dashed circles).

effect of atmospheric scintillation (rapid fluctuations of the signal's amplitude and phase, due to irregularities in the refractive index) and gas attenuation due to the longer path to the satellite [6]. The signal is also subject to multipath fading, due to ducting and sea-surface reflections. Typically, ducting occurs in unusual atmospheric conditions, where the temperature increases with height over some limited range, creating a temperature inversion and sub-refractive conditions [7]. If not properly considered, the above-mentioned propagation impairments can significantly affect the availability of a geostationary satellite at low elevation angles. This may further reduce the coverage of a geostationary satellite in the polar region satisfying a given quality-of-service (QoS).

Low-Earth orbit satellite systems, such as Iridium, could be used for communication in the polar region, but the offered data rates are low: around 2.4 kbps and 10 kbps for dial-up and direct Internet connections, respectively. The data rate is expected to increase with the second generation of the Iridium system. However, the connection cost may still be expensive.

3. Potential Low-Cost Solutions

In this section, we present three potential low-cost broadband-communication-system solutions for the polar region.

3.1 Store-and-Forward Method

Polar-orbiting satellites circle the Earth at a typical altitude of 850 km in a north-to-south (or vice-versa) path, passing

over the poles in their continuous flight. The orbital period is slightly greater than 100 min, with just over 14 orbits in a day. As known from Earth observations, polar-orbiting satellites, such as RADARSAT and Envisat, already have high-bandwidth capabilities for downloads (a maximum data rate of 85 Mbps (recorded) or 105 Mbps (in real time) for RADARSAT, and 200 Mbps for Envisat), and might be used for communication purposes for the polar region using a store-and-forward method.

A more-continuous downloading/uploading of information might be achieved by placing an Earth station connected to a geostationary satellite (backbone) in a location where all of the 14 daily passes of the polar-orbiting satellites are covered (e.g., in Svalbard, Norway) [8]. For example, user terminals with elevation angles of 5° located above around 75° north could then have near-real-time data transfer. In this case, data from/to user terminals above around 75° north (i.e., outside the coverage area of geostationary satellites; see Figure 3) to/from the Earth station (located within the coverage area of geostationary satellites) would be transferred via a polar-orbiting satellite (see Figure 4). This method may enable us to provide near-real-time broadband services by picking up bursty data from vessels, and forwarding the data to the nearest ground terminal. Similarly, data uploaded from a ground terminal would be stored and forwarded to vessels. From the Earth station, the data would be further distributed using a geostationary satellite to customers all over the world. For user terminals located below around 75° north, a geostationary satellite would be directly used to provide communication services. In this way, a low-cost alternative for broadband communications in the polar region might be obtained. In general, the store-and-forward method might even be a price-competitive solution, even in regions with geostationary coverage.

The limitation with this approach is that complete real-time data transfer can not be achieved. In addition, high-capacity communication requires a stable, point-to-point connectivity for a certain amount of time, which might require mechanically or electrically stabilized antennas on the user terminals. However, stable pointing towards the satellite might be difficult, due to the high seas and large waves encountering in polar regions. This may result in continuous “off” and “on” connections between the vessel and the satellite.

3.2 High-Frequency Multiple-Input Multiple-Output (HF MIMO)

The use of multiple antennas at both the transmitter and receiver, referred to as multiple-input multiple-output (MIMO), can significantly increase the system’s performance by exploiting the multipath propagation of the channel [9]. By using the spatial dimension of a communication link, MIMO systems can achieve significantly higher data rates than traditional SISO channels. The existence of multiple propagation paths due to ionospheric refraction and reflection from the Earth’s surface makes the use of MIMO techniques suitable for HF signals. The concept of MIMO has been focused on higher-frequency bands; there has been little work reported on HF MIMO. From measurements, it was shown in [10-12] that significant increases in data rate can be obtained in HF radio systems utilizing MIMO techniques. A considerable reduction in the required antenna spacing by using compact, collocated, heterogeneous antenna arrays was also reported [11]. Further increases in performance might also be achieved by using both space and polarization diversities. In general, the use of HF MIMO may provide long-range communication (covering the polar region, as shown in Figure 2) at a much higher data rate and availability compared to a SISO HF signal. Such a system might use a terrestrial or a geostationary satellite link (below around 75° to 81° north, depending on the elevation angle) as a backbone.

It was reported in [13] that HF signals refracted from the northerly ionosphere exhibited Doppler shifts (changes in wave frequency caused by time-varying ionospheric refraction), and angular and delay spreads that significantly exceeded those observed over mid-latitude paths. These effects thus need to be taken into account when designing HF MIMO for the polar region.

3.3 Wide-Area Mesh Network

Mesh networks are built on a mix of fixed and mobile nodes, interconnected via wireless links, to form a multi-hop ad-hoc network. User devices dynamically join the network and act as both user terminals and routers for other devices, consequently further extending the network’s coverage [14, 15]. A wide-area mesh network could be created in the polar region by installing communication infrastructure on remote islands, in wind farms, on buoys, vessels, and offshore installations (see Figure 5). Buoys can drift (e.g., for observation of the oceanic drift) or be stationary. These may create a self-configuring and self-organizing routing and network structure that satisfies a given quality-of-service [16]. Creating such a network requires solving several technological challenges. The distance between the nodes and their ability to move may create a delay in the network, which might be addressed using delay-tolerant

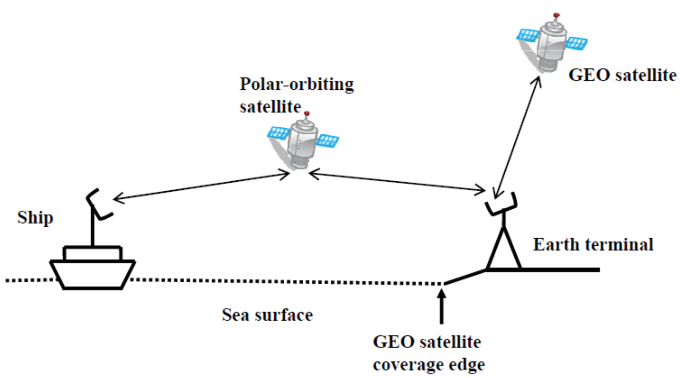

Figure 4. Data from/to a vessel is forwarded by a polar-orbiting satellite, using a store-and-forward method, to/from an Earth station connected to a geostationary-satellite backbone.

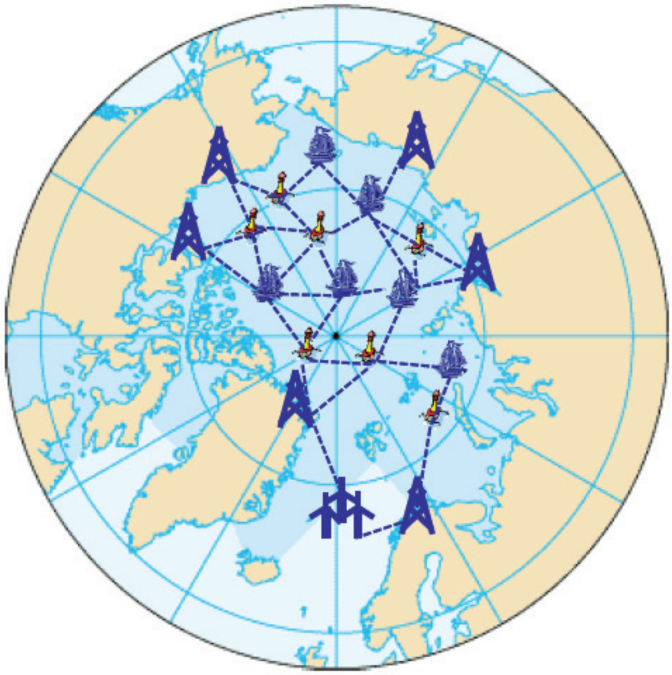

Figure 5. Coastal access points, buoys, ships, and wind farms creating a wide-area mesh network in the polar region.

networking (DTN) [17]. In addition, the drift of nodes would cause volatile network links, requiring a continuously updating routing algorithm. In [18], data management in a network of drifting nodes over the ocean was reported. The movement of nodes may also result in clusters, and leave sparsely covered areas that reduced the overall area coverage. In this case, drifting buoys could correct their positions to achieve a well-distributed node structure over the ocean. Mechanisms must thus be developed that allow nodes to correct their position.

For radio transmission between the different nodes, technologies such as WiMAX might be used, enabling high-data-rate communication. In this case, in order to satisfy a given quality-of-service, propagation impairments caused by the swell of waves, sea-surface reflections, and signal fading due to the movements of vessels and buoys, have to be taken into account.

4. Comparison

In Section 3, we presented three possible low-cost broadband communication solutions for the polar region. Each proposed solution has its own implications for system performance. In this section, we discuss the advantages and limitations of each solution, seen from bandwidth, delay, and implementation-cost points of view.

As mentioned in Section 3.1, polar-orbiting satellites have large available bandwidth. The store-and-forward method is thus believed to be the most bandwidth-efficient solution. The implementation cost for such a system is mostly related to the installations of Earth terminals for the uploading and downloading of data, and the need for stabilized antennas at the user terminals. However, such a system will suffer from relatively large delays due to limited passing of the satellite, especially for locations that are farther away from the North Pole region.

To the contrary, the HF MIMO solution does not suffer from any delay, and the implementation cost is mostly related to the installation of compact, collocated, heterogeneous antenna arrays at the transmitter and the receiver. In addition, sufficient capacity can be achieved by utilizing MIMO diversity techniques, enabling broadband communication. On the other hand, the implementation cost for the third option, i.e., a wide-area mesh network, is related to the installation of communication infrastructure on remote islands, in wind farms, on buoys, vessels, and offshore installations. A wide-area mesh network solution would use high-capacity radio – such as WiMAX – for transmission between the different nodes, resulting in high-data-rate communications. However, the distance between the network nodes and their ability to move may create a delay in the network, which might be addressed using delay-tolerant networking.

Depending on the type of service to be provided (which may, for example, require real-time, near-real-time, non-real-time, large bandwidth, etc.) and the budget needed to roll out and operate the system, operators may choose one of the proposed low-cost broadband communication solutions for the polar region.

5. Conclusion

The demand for a reliable high-capacity communication system in the polar region is expected to increase when the Northwest, Northeast and North-North Passages are open for transportation. The system needs to support the increasing activities related to the fishing, oil, and gas industries in the polar region. In this paper, we discussed the communication challenges and limitations in the polar region, and proposed three possible low-cost broadband communication solutions that could be implemented. The proposed solutions were a store-and-forward method, using polar-orbiting satellites (this might even be a solution that is price competitive even in regions with geostationary coverage); HF MIMO; and a wide-area mesh network solution, using high-capacity radio such as WiMAX.

In addition, we discussed the advantages and limitations of each solution, seen from the bandwidth, delay, and implementation-cost points of view. The store-and-forward method using polar-orbiting satellites has large bandwidth, but may suffer from delay. The solution that uses HF MIMO has lower bandwidth compared to the store-and-forward method, but does not have any delay. The approach that uses a wide-area mesh network has relatively large bandwidth, but may suffer from network delay that could be addressed using delay-tolerant networking.

Generally, depending on the type of service (which may, for example, require real-time, near-real-time, non-real-time, large bandwidth, etc.) and the available budget, operators may choose one of the proposed low-cost broadband communication solutions for the polar region.

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7. References

1. R. B. Alley et al., "Past Climate Variability and Change in the Arctic and at High Latitudes," Final Report, Climate Change Science Program, Synthesis and Assessment Product 1.2, 2009.

2. I-Nord, "A Holistic Information System for Monitoring of Maritime Security, Marine Environment and Marine Resources of the Nordic Seas and Arctic Ocean," Final report, 2009, available at http://www.regjeringen.no.

3. K. W. Gurgel, H. H. Essen, and S. P. Kingsley, "High-Frequency Radars: Physical Limitations and Recent Developments," *Coastal Engineering*, **37**, 3-4, August 1999, pp. 201-218.

4. R. A. Poisel, *Introduction to Communication Electronic Warfare Systems*, Norwood, MA, Artech House, 2002.

5. S. D. Ilcev, *Global Mobile Satellite Communications for Maritime, Land and Aeronautical Applications*, Dordrecht, Springer, 2005.

6. O. Paul and E. Vilar, "Measurement and Modeling of Amplitude Scintillation on Low-Elevation Earth-Space Path and Impact on Communication Systems," *IEEE Transactions on Communication*, **34**, 8, August 1986, pp. 774-780.

7. S. R. Saunders, *Antennas and Propagation for Wireless Communication Systems*, New York, Wiley, 2007.

8. Envisat, "Polar Satellite Services from Telenor – Reliable Near Real-Time Data Delivery via Satellite," *Nordic Space Activities*, **46**, 2004.

9. G. J. Foschini and M. J. Gans, "On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas," *Wireless Personal Communications*, **6**, 3, 1998, pp. 311-335.

10. D. S. Gunashekar, E. M. Warrington, S. Salous, S. M. Feeney, N. M. Abbasi, L. Bertel, D. Lemur, and M. Oger, "Investigations into the Feasibility of Multiple Input Multiple Output Techniques within the HF Band: Preliminary Results," *Radio Science*, **44**, RS0A19, August 2009, doi:10.1029/2008RS004075.

11. D. S. Gunashekar, E. M. Warrington, S. M. Feeney, S. Salous, and N. M. Abbasi, "MIMO Communications within the HF Band Using Compact Antenna Arrays," *Radio Science*, **45**, RS6013, December 2010, doi:10.1029/2010RS004416.

12. P. M. Ndao, Y. Erhel, D. Lemur, and J. L. Masson, "Design of a High Frequency (3 - 30 MHz) Multiple-Input Multiple-Output System Resorting to Polarisation Diversity," *IET Microwave Antennas and Propagation*, **5**, 11, August 19, 2011, pp. 1310-1318.

13. M. E. Warrington, A. J. Stocker, and D. R. Siddle, "Measurement and Modeling of HF Channel Directional Spread Characteristics for Northerly Paths," *Radio Science*, **41**, RS2006, April 2006, doi:10.1029/2005RS003294.

14. R. Bruno, M. Conti, and E. Gregori, "Mesh Networks: Commodity Multihop Ad Hoc Networks," *IEEE Communication Magazine*, **43**, March 2005, pp. 123-131.

15. I. F. Akyildiz and X. Wang, *Wireless Mesh Networks*, Chichester, UK, John Wiley, 2009.

16. M. C. Jaeger and G. Muhl, "A Floating Backbone for Internet Over the Ocean," *IEEE Distributed Systems*, **9**, 12, January 2008, doi:10.1109/MDSO.2008.33.

17. V. Cerf et al., "Delay-Tolerant Networking Architecture," IETF RFC 4838, April 2007, available at http://www.ietf.org/rfc/rfc4838.txt.

18. S. Nittel, N. Trigoni, and K. Ferentinos, "A Drift-Tolerant Model for Data Management in Ocean Sensor Networks," Proceedings of the 6th ACM International Workshop on Data Engineering for Wireless and Mobile Access (MobiDe 07), 2007, pp. 49-57.

Introducing the Author

Michael Cheffena received the MSc in Electronics and Computer Technology from the University of Oslo, Norway, in 2005; and the PhD from the Norwegian University of Science and Technology (NTNU), Trondheim, Norway, in 2008. For one year, he was a visiting researcher at the Communications Research Centre (CRC), Canada. From 2009 to 2010, he did a post-doctoral study at the University Graduate Center (UNIK), Kjeller, Norway. From 2010 to 2011, he was a Post-Doctoral Fellow at the French Space Agency (CNES), Toulouse, France. Currently, he is an Associate Professor at Gjøvik University College, Norway. His research interests include modeling and prediction of radio channels for both terrestrial and satellite links.